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Sclerotinia sclerotiorum impacts on host crops

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by

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DEDICATION

This work is dedicated to my parents, Dan and Dawn Sawatzke, and my husband, Brad Ficker. Without your support, sacrifices, and encouragement throughout my academic career, and beyond, I would not have been able to achieve my goal of obtaining my Master of Science degree in Agronomy. I hope to always make you as proud of me as I am of you.

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ABSTRACT

Many growers throughout the world have been battling large yield losses due to a disease caused by the fungus *Sclerotinia sclerotiorum*. With worldwide distribution and a wide host range, gaining basic understanding of *Sclerotinia sclerotiorum* will prove beneficial when attempting to forecast disease outbreaks caused by the pathogen. The variability in host creates large variation in infection sites, sampling timing, favorable environmental conditions, and effective management strategies. This is a review of current literature covering the variables associated with the disease and its host species utilized in scouting and preventing further epidemics. The beginning literature covers the history and importance of the disease. It is followed by literature explaining the signs, symptoms, hosts and locations, and the lifecycle of *Sclerotinia sclerotiorum*. To conclude, literature was compiled for the best ways to scout and assess the damage by the fungal pathogen and which management practices would be most effective. No management strategy is 100% effective, integrating multiple approaches of cultural, chemical, and biological will be the best management practices to prevent diseases caused by *Sclerotinia sclerotiorum*.

INTRODUCTION

Sclerotinia sclerotiorum is a devastating fungal pathogen that causes substantial losses to a wide range of hosts worldwide. The fungus causes millions of dollars' worth of damage annually affecting both yield and seed quality. The broad host range is important because it restricts the methods of control and suppression that can be used.

Disease symptoms vary by host species but typically begins with water-soaked lesions. Signs of the pathogen are apothecia, mycelium, and sclerotia, the overwintering structure. The sclerotia remain viable in the soil for many years. If the sclerotia are close to the soil surface with a susceptible host, they may germinate depending on the environmental conditions. Many environmental factors influence the infection by *Sclerotinia sclerotiorum*, especially temperature and moisture levels. By understanding how the pathogen infects hosts, disperses, and survives, we are able to scout for disease incidences. This can help create disease-forecasting models to prevent *Sclerotinia sclerotiorum* epidemics.

It is difficult to control *Sclerotinia sclerotiorum* because of the long-term persistence of sclerotia and unpredictability of infection. It is important to match the management sequences with the growth stage of the host species while integrating multiple management strategies including cultural practices, pesticides, and biological control. Utilizing a multitude of management approaches simultaneously offers the best opportunity to prevent the destruction from the pathogen *Sclerotinia sclerotiorum*.

History

Sclerotinia sclerotiorum has had a long history and this includes multiple names. More than 60 names have been used for the disease caused by this fungal pathogen since it was discovered in 1837 (Bolton et al., 2006). Madame M.A. Libert was the first to name *Sclerotinia sclerotiorum* but used the binomial *Peziza sclerotiorum* until it was renamed *Sclerotinia libertiana* by Fuckel (Purdy, 1979). There was discussion of speciation within the genus based on mycelial germination, mycelial interactions, various fungus structures, and the measurements of some of the structures including ascospores and apothecia.

After the first report of *Sclerotinia sclerotiorum* was published in Delaware in 1890 due to serious loss of both *Lactuca sativa* (lettuce) and other glasshouse crops, additional species were named to *Sclerotinia sclerotiorum*, *Sclerotinia libertiana*, and *Sclerotinia minor* based on the size of the sclerotia and the associated hosts. These additional species were: *Sclerotinia intermedia, Sclerotinia serica, Sclerotinia trifoliorum,* and *Sclerotinia sativa* (Purdy, 1979). After the devastation from the disease lettuce drop caused by *Sclerotinia sclerotiorum*, researchers were able to conclude that there were differences amongst species. Some of the differences noted were size and amount of sclerotia produced, how cultivation and other conditions affect the production of the apothecia, the distribution and spreading patterns, and infection levels based on soil moisture (Abawi and Grogan, 1979).

Only three species remain: *Sclerotinia minor, Sclerotinia trifoliorum,* and *Sclerotinia sclerotiorum* (Bolton et al., 2006). The species are differentiated based on their host crops. *Sclerotinia sclerotiorum* is the most nonspecific species occurring in both Gymnospermae and Angiospermae classes, *Sclerotinia minor* only infects host crops in the Dicotyledonae and Monocotyledonae subclasses of the division Spermatophyta within the Angiospermae class, and *Sclerotinia trifoliorum* has a host range limited to forage legumes (Saharan and Mehta, 2008).

Agronomic Importance

In the United States, *Sclerotinia sclerotiorum* can cause over $200 million in losses annually (Bolton et al., 2006). The yield loss caused by *Sclerotinia sclerotiorum* ranges from 0-100% and is typically estimated by disease incidence because of the varying host range (Purdy, 1979). White mold of *Glycine max* (soybeans), white stem rot of *Brassica napus* (canola-mustard), *Sclerotinia* disease of *Papaver somniferum* (poppy), and *Sclerotinia* rot in *Lens culinaris* (lentils) and *Cicer arietinum* (chickpeas) are some of the common diseases associated with *Sclerotinia sclerotiorum* (Saharan and Mehta, 2008). Some other common diseases are dollar spot in *Poaceae* (turf), basal stem rot in *Helianthus annuus* (sunflower), and white mold of *Brassica oleracea var. capitate* (cabbage) and *Solanum lycopersicum* (tomato) (Heffer Link and Johnson, 2007).

For soybeans, yield loss is noticed by reduction in the seed number and weight (Mueller et al., 2015a). The state of North Dakota grows 90% of the canola grown in the

United States. In North Dakota, it was estimated that between 1991 and 2002, there was an economic impact from *Sclerotinia sclerotiorum* of $94 million (Del Río et al., 2007). Other crops that have taken large economic losses in the United States are: lettuce, *Arachis hypogaea* (peanut), *Solanum tuberosum* L. (potato), sunflower, and tomato (Purdy, 1979).

Although yield is used as a measurement, *Sclerotinia sclerotiorum* can also cause economic losses through seed quality and production. Reductions in quality may be increased foreign material, reduced germination, or seed components like oil and protein in soybeans (Mueller et al., 2015a). Also, seed lots may be contaminated with sclerotia providing inoculum in fields that are not yet infested (Heffer Link and Johnson, 2007). Fortunately, total losses are not experienced continuously because sclerotia may not germinate some years based on soil conditions (Purdy, 1979).

IDENTIFICATION

Sclerotinia sclerotiorum takes on many different forms depending on the growth stage of both the host and the fungus. It is important to note that signs are different from symptoms in the fact that the signs are the actual presence of the fungus parts on a host plant and not the reaction of the host plant to the fungus (Bos and Parlevliet, 1995).

Signs of fungus

Some of the earliest signs are apothecia produced from the overwintering structures of *Sclerotinia sclerotiorum* in the soil (USDA, 2015). The apothecia is a tan, mushroom-like structure that hosts the ascospores which are utilized for dispersion and infection (Schwartz and Steadman, 1978). The over-wintering structure of *Sclerotinia sclerotiorum* is a hard, black structure called sclerotia and can be found inside or outside the affected plant (Mueller et al., 2015). Another characteristic sign of *Sclerotinia sclerotiorum* is mycelium, a white and cotton-like structure, that will later form clumps and later turn into the sclerotia (Heffer and Johnson, 2007).

Some of the signs of *Sclerotinia sclerotiorum* may resemble other diseases. The apothecia tends to mimic the *Cyathus striatus*, bird’s nest fungus, or other fruiting fungal structures and the mycelial growth that is a natural part of decomposition may be mistaken for the mycelium of *Sclerotinia sclerotiorum* (Giesler, 2016).

Symptoms in host crops

Although one will not typically see symptoms in the host crop right away, infection occurs early in the plant's development allowing the hyphae to infect the host (Heffer and Johnson, 2007). In fact, most symptoms will not be expressed until the plant is dying (Giesler, 2016).

The first symptom is lesions that appear to be water soaked on the leaves, stems, and branches (Mueller et al., 2015a). These lesions may also be light brown in color but will expand turning into a greyish white color. Of the host plants that have girdled stems, such as canola, the plant will wilt and prematurely ripen to become noticeably different in color than the non-infected green plants surrounding it ("Sclerotinia stem rot" - Canola Council of Canada). As the fungal activity continues within the host, the plant will appear bleached in color with plant parts showing shredded characteristics due to tissue breakdown (Purdy, 1979). It is common to see *Sclerotinia sclerotiorum* occur in patches within fields due to varying environmental conditions (Mueller et al., 2015b).

HOSTS AND LOCATIONS

Generally, *Sclerotinia sclerotiorum* occurs in cool and moist areas of the world (McDonald et al., 2004). The fungus has a wide host range of about 400 species and worldwide distribution, even with the knowledge in optimum temperature and moisture levels, it is still difficult to forecast infection of *Sclerotinia sclerotiorum* (Twengström et al., 1998).

Crop and weed hosts of *Sclerotinia sclerotiorum*

Although there has been considerable variation in hosts reported, the most recent host index indicates that there are 42 subspecies, 408 species, 278 genera, and 75 families of plants that are infected by *Sclerotinia sclerotiorum* (Saharan and Mehta, 2008). *Sclerotinia sclerotiorum* has been reported on all continents and it is probable that the pathogen survives in every country (Purdy, 1979).

Table 1. *Sclerotinia sclerotiorum* Host Range (Adapted from Boland and Hall, 1994.)

Latin binomial	Common name
POACEAE (Grass family)	
Avena sp.	Oats
Digitaria sanguinalis (L.) Scop.	Large crab grass

Hardeum vulgare L.	Barley
Pennisetum americanum Schum.	Pearl millet
Secale cereale L.	Rye
Setaria viridis (L.) Beauv.	Green foxtail
Sorghum bicolor (L.) Moench	Broomcorn
Sorghum vulgare Pers.	Sorghum
Triticum aestivum L.	Wheat
Zea sp.	Maize

FABACEAE (Pulse family)

Apios americana Medic.	Groundnut
Arachis hypogaea L.	Peanut
Astragalus sinicus	Milk vetch
Cicer arietinum L.	Chick pea
Caronilla varia L.	Crown vetch
Crotalaria juncea L.	Sun hemp
Desmodium triflorum L. D.C.	Undetermined
Dolichos biflorus L.	Horse gram
Dolichos lablab L.	Egyptian bean
Glycine max (L.) Merrill	Soybean
Lathyrus odoratus L.	Sweet pea
Lathyrus sativus L.	Grass pea
Lens culinaris Medic.	Lentil
Lotus corniculantus L.	Bird’s-foot trefoil
Lotus sp.	Undetermined
Lupinus angustifolius L.	European blue lupine
Lupinus nootkatensis Donn.	Lupine
Lupinus perennis L.	Sundial lupine
Lupinus polyphyllus Lindl.	Washington lupine
Lupinus sp.	Lupine
Medicago hispida Gaertn.	Bur clover
Medicago lupulina L.	Black medick
Medicago sativa L.	Alfalfa
Melilotus alba Desr.	White sweet clover
Melilotus indica (L.) All.	Sweet clover
Melilotus officinalis (L.) Pall.	Yellow sweet clover
Melilotus sp.	Sweet clover
Onobrychis vicifolia Scop.	Sainfoin
Phaseolus cocccineus L.	Scarlet runner bean
Phaseolus limensis Macfady	Lima bean
Phaseolus lunatus L.	Civet bean
Phaseolus radiatus L.	Green bean
Phaseolus vulgaris L.	Kidney bean
Pisum sativum L.	Pea
Pisum sativum L. var. *arvense* (L.) Poir.	Field pea

Table 1. (continued)

Latin binomial	Common name
Stylosanthes hamata (L.) Taub.	Caribbean stylo
Stylosanthes humilis Kunth.	Townsville stylo
Stylosanthes guianensis (Aubl.) Sw.	Brazilian stylo
Trifolium alexandrinum L.	Egyptian clover
Trifolium hybridum L.	Alsike clover
Trifolium incarnatum L.	Crimson clover
Trifolium procumbens L.	Least hop clover
Trifolium pratense L.	Red clover
Trifolium pratense L. var. *praecox*	Undetermined
Trifolium pratense L. var. *seratinum*	Undetermined
Trifolium repens L.	White clover
Trifolium sp.	Clover
Trifolium subterraneum L.	Subterranean clover
Trifolium wormskjoldii Lehm.	Sierra clover
Trigonella foenum-graecum L.	Fenugreek
Trigonella sp.	Fenugreek
Vicia faba L.	Broad bean
Vicia sativa L.	Spring vetch
Vicia sp.	Vetch
Vicia villosa Roth.	Hairy vetch
Vigna angularis (Willd.) Ohwi & Ohashi	Azuki bean
Vigna mungo (L.) Hepper	Black gram
Vigna radiata (L.) Wilcz.	Mung bean
Vigna unguiculata (L.) Walp.	Yard-long bean
Vigna unguiculata (L.) Walp. sub sp. *sesquipedalis*	Cowpea
BRASSICACEAE (Mustard family)	
Arabidopsis thaliana (L.) Heynh.	Mouse-ear cress
Armoracia Rusticana Gaertn., Mey. & Scherb.	Horseradish
Barbarea vulgaris R Br.	Yellow rocket
Brassica campestris L.	Bird rape
Brassica campestris L. var. *napobrassica* (L.) D.C.	Rutabaga (Swede)
Brassica chinensis L.	Pak-choy
Brassica hirta Moench.	White mustard
Brassica juncea (L.) Coss.	Leaf mustard
Brassica juncea (L.) Coss. var. *crispifolia* Bailey	Curled mustard
Brassica kaber (D.C.) Wheeler	Charlock
Brassica napus L.	Rape
Brassica nigra (L.) Koch	Black mustard
Brassica oleracea L. var. *acephala* D.C.	Kale
Brassica oleracea L. var. *botrytis* L.	Broccoli
Brassica oleracea L. var. *botrytis* L.	Cauliflower
Brassica oleracea L. var. *capitata* L.	Cabbage

Table 1. (continued)

Latin binomial	Common name
Brassica oleracea L. var. *caulorapa* D.C.	Knolkhol
Brassica oleracea L. var. *gemmifera* Zenk.	Brussels sprouts
Brassica oleracea L. var. *gongylodes* L.	Kohlrabi
Brassica oleracea L. var. *ramosa* Alef.	Undetermined
Brassica oleracea L. var. *viridis* L.	Kale
Brassica pekinensis (Lour.) Rupr.	Chinese cabbage
Brassica rapa L.	Turnip
Brassica rugosa Lai	Undetermined
*Capsella bursa-pastoris (*1.) Medic.	Shepherd's purse
*Cardamine heterophylla (*Forst.) Schutz	Bittercress
Cheiranthus chieri L.	Wallflower
Crambe abyssinica Hochst. ex R E. Fr.	Kale
Descurainia sophia (L.) Webb.	Tansy mustard
Draba sp.	Dill
*Eruca vesicaria (*L.) Cav. (as E. sativa Mill)	Rocket-salad
Erysimum asperum (Nutt.) D.C.	Western wallflower
Erysimum hieraciifolium	Wallflower
Lberis amara L.	Rocket candytuft
Lberis umbellata L.	Globe candytuft
Lepidium sativum L.	Garden cress
Lepidium virginicum L.	Poor-man's pepper grass
Lobularia maritima (L.) Deso.	Sweet alyssum
Matthiola incana (L.) Br.	Common stock
Matthiola sp.	Stock
Nasturtium officinale Br.	Watercress
Raphanus raphanistrum L.	Wild radish
Raphanus sativus L.	Garden radish
Raphanus sativus L. var. *hortensis* Makino	Undetermined
Rorippa sylvestris (L.) Besser	Creeping yellow cress
Rorippa sp.	Yellow cress
Sisymbrium officinale (L.) Scop.	Hedge mustard
Thlaspi arvense L.	Penny cress
CUCURBITACEAE (Gourd family)	
Citrullus lanatus (Thunb) Matsum & Nakai	Watermelon
Citrullus vulgaris var. *citroides* (Bailey) Mansf.	Citron
Citrullus vulgaris var. *fistulosus*	Undetermined
Cucumis anguria L.	Gherkin
Cucumis melo L.	Melon
Cucumis melo L. var. *cantaloupensis* Naud.	Undetermined
Cucumis melo L. var. *makuwa* Makino	Undetermined
Cucumis melo L. var. *reticulatus* Naud.	Muskmelon
Cucuinis melo L. var. *utilissimus*	Undetermined

Table 1. (continued)

Latin binomial	Common name
Cucumis sativus L.	Cucumber
Cucurbita maxima Duchesne	Winter squash
Cucurbita moschata Duchesne	Undetermined
Cucurbita pepo L.	Pumpkin
Cucurbita pepo L. var. *melopepo* (L.) Alef.	Bush pumpkin
Cucurbita pepo L. var. *ovifera* (L.) Alef.	Yellow-flowered gourd
Lagenaria siceraria (Mol.) Standl.	Bottle gourd
Luffa cylindrica Mill.	Loofah
SOLANACEAE (Nightshade family)	
Capsicum annuum L.	Pepper
Capsicum frutescens L.	Tabasco
Capsicum frutescens L. cv. 'grossum'	Sweet pepper
Cyphomandra betaceae Sendt	Tree tomato
Datura stramonium L.	Jimsonweed
Datura innoxa Mill.	Angel's trumpet
Hyoscyamus niger L.	Henbane
Lycopersicon esculentum Mill.	Tomato
Nicandra physalodes (L.) Gaertn.	Apple of Peru
Nicotiana rustica L.	Wild tobacco
Nicotiana tabacum L.	Tobacco
Petunia axillaris (Lam.) BSP	Whitemoon petunia
Petunia hybrida Hort.	Garden petunia
Petunia spp.	Petunia
Physalis angulata L.	Undetermined
Physalis peruviana L.	Cape gooseberry
Schizanthus pinnatus	Butterfly flower
Schizanthus retusus Hook.	Butterfly flower
Schizanthus sp.	Butterfly flower
Schizanthus wisetonensis Hort.	Undetermined
Solanum chacoense Bitter	Undetermined
Solanum citrullifolium Br.	Melon leaf nightshade
Solanum elaeagnifolium Cav.	Silver leaf nightshade
Solanum guitoense Lam.	Lulu
Solanum melongena L.	Eggplant
Solanum melongena var. *esculentum* Nees.	Eggplant
Solanum nigrum L.	Black nightshade
Solanum torvum Swartz	Devil's fig
Solanum tuberosum L.	Potato
CHENOPODIACEAE (Goosefoot family)	
Beta vulgaris L.	Beet
Beta vulgaris L.	Sugar beet
Chenopodium album L.	Lamb's-quarters

Table 1. (continued)

Latin binomial	Common name
Chenopodium album L. var. *centrorubrum* Makino	Undetermined
Spinacia oleracea L.	Spinach
CONVOLVULACEAE (Convolvulus family)	
Convolvulus arvensis L.	Field bindweed
Convolvulus sp.	Bindweed
Ipomoea batatus (L.) Lam.	Sweet potato
LILIACEAE (Lily family)	
Allium cepa L.	Onion
Allium sativum L.	Garlic
Asparagus officinalis L. var. *altilis* L.	Asparagus
Asphodelus tenuifolius Cav.	Asphodel
Lilium candidum L.	Madonna lily
Lilium longiflorum Thurb.	Trumpet lily
Lilium sp.	Lily
Trillium foetidissimum Freeman	Red lily
Tulipa gesneriana L.	Tulip
Tulipa sp.	Tulip
APIACEAE (Parsley family)	
Aegopodium spp.	Goutweed
Anethum graveolens L.	Dill
Angelica archangelica L.	Angelica
Apium graveolens L. var. *dulce* (Mill.) Pers.	Celery
Apium graveolens L. var. *rupaceum* (Mill.) Gaud. Beaup.	Celeriac
Carum carvi L.	Caraway
Conium maculatum L.	Poison hemlock
Coriandrum sativum L.	Coriander
Daucus carota L.	Carrot
Foeniculum vulgare Mill.	Fennel
Foeniculum vulgare Mill. var. *dulce* Batt. & Trab.	Fennel
Pastinaca sativa L.	Parsnip
Petroselinum crispum (Mill.) Nym. ex Hill	Parsley
Pimpinella anisum L.	Anise
Pimpinella sp.	Undetermined
LINACEAE (Flax family)	
Linum flavum L.	Golden flax
Linum usitatissimum L.	Common flax
MALVACEAE (Mallow family)	
Abelmoschus esculentus (L.) Moench.	Okra
Abutilon theophrasti Medick	Velvetleaf
Alcea ficifolia (L.) Cav.	Antwerp hollyhock
Alcea rosea L.	Hollyhock

Table 1. (continued)

Latin binomial	Common name
Gossypium hirsutum L.	Upland cotton
Gossypium sp.	Cotton
Hibiscus cannabinus L.	Indian hemp
Hibiscus rosa-sinensis L.	Chinese hibiscus
Hibiscus sabdariffa L.	Jamaica sorrel
Lliamna rivularis (Dougi.) Greene	Undetermined
Lavatera arborea L.	Tree mallow
Malvaviscus arboreus Cay.	Wax mallow
Malvaviscus sp.	Sleepy mallow
PEDALIACEAE (Pedalium family)	
Sesamum indicum L.	Sesame
ROSACEAE (Rose family)	
Fragaria ananassa Duchesne var. *ananassa* Bailey	Strawberry
Fragaria sp.	Strawberry
Malus sylvestris Mill.	Apple
Malus sp.	Apple
Prunus americana Marsh.	American plum
Prunus amygdalus Batsch	Almond
Prunus armeniaca L.	Apricot
Prunus domestica L.	Garden plum
Prunus persica (L.) Batsch	Peach
Prunus sp.	Undetermined
Pyrus communis L.	Pear
Rosa sp.	Rose
Rubus sp.	Raspberry
RUTACEAE (Rue family)	
Citrus aurantifolia Christm.	Lime
Citrus aurantifolia Christm. var. *dulcis*	Lime
Citrus aurantium L.	Seville orange
Citrus latifolia Tanaka	Persian lime
Citrus limon Burm.	Citron
Citrus maxima (Burm.) Merril	Pumelo
Citrus medica L.	Citron
Citrus paradisi Macfady	Grapefruit
Citrus reticulata Blanco	Mandarin orange tree
Citrus sinensis Osbeck.	Sweet orange
Citrus spp.	Undetermined
VITACEAE (Vine family)	
Vitis vinifera L.	European wine grape
MORACEAE (Mulberry family)	
Ficus carica L.	Fig
Ficus magnifolia Muell	Magnolia-leaf fig

Table 1. (continued)

Latin binomial	Common name
Morus alba L.	White mulberry
Morus spp.	Mulberry
EUPHORBIACEAE (Spurge family)	
Euphorbia dentata Michx.	Toothed spurge
Euphorbia pulcherrima Willd. ex. Klotzsch	Poinsettia
Euphorbia serphyllifolia Pers.	Thyme-leaved spurge
Euphorbia spp.	Undetermined
Ricinus communis L.	Castor bean
Scabiosa sp.	Sweet scabious
MUSACEAE (Banana family)	
Musa paradisiaca L.	Edible plantain
Musa spp.	Banana
ANNONACEAE (Custard-Apple family)	
Annona squamosa L.	Sugar apple
Asimina sp. Adans Pawpaw	
PINACEAE (Pine family)	
*Chamaecyparis lawsoniana (*Murr.) Parl.	Lawson white cedar
Cryptomeria japonica (L f.) Don.	Japanese cedar
Larix kaempferi (Lamb.) Carriere	Japanese larch
Pinus densiflora Slebd.& Zucc.	Japanese red pine
IRIDACEAE (Iris family)	
Freesia spp. Eckl. Ex Klatt.	Undetermined
Gladiolus spp.	Gladiolus
Iris spp.	Iris
Iris xiphioides Ehrh.	English iris
CAMPANULACEAE (Bluebell family)	
Campanula medium L.	Canterbury bells
Campanula persicifolia L.	Willow bellflower
Campanula pyrimidalis L.	Undetermined
Campanula rapunculoides L.	Creeping bellflower
Campanula sp.	Undetermined
Lobelia erinus L.	Edging lobelia
CANNABACEAE (Hemp family)	
Cannabis sativa L.	Marijuana, hemp
Humulus lupulus L.	Common hop
Humulus sp.	Hop
LAMIACEAE (Mint family)	
Lamium amplexicaule L.	Henbit
Lamium spp.	Deadnettle
Mentha piperita L.	Peppermint
Mollucella laevis L.	Bells of Ireland
Ocimum basilicum L.	Basil

Table 1. (continued)

Latin binomial	Common name
Perilla frutescens (L.) Britt. var. *japonica* (Hassk.) Hara	Undetermined
Physostegia virginiana (L.) Benth.	Obedience
Salvia sp.	Sage
Solenostemon scutellarioides (L.) Codd.	Coleus
Stachys floridana Shuttleworth ex. Benth.	Undetermined
PAPAVERACEAE (Poppy family)	
Argemone sp.	Argemony
Eschscholzia california Cham.	California poppy
Eschscholzia spp.	California poppy
Glaucium flavum Crantz.	Undetermined
Papaver somniferum Crantz.	Opium poppy
Romneya sp.	Matilija poppy
PASSIFLORACEAE (Passionflower family)	
Passiflora edulis Sims	Purple granadilla
Passiflora sp.	Passion fruit
PLANTAGINACEAE (Plantain family)	
Plantago lanceolata L.	Buckhorn
POLEMONIACEAE (Polemonium family)	
Phlox drummondii Hook	Annual phlox
Phlox sp.	Phlox
POLYGONACEAE (Buckwheat family)	
Fagopyrum esculentum Moench.	Buckwheat
Fagopyrum tataricum Gaertn.	Buckwheat
Rheum rhaponticum L.	Rhubarb
Rumex crispus L.	Yellow dock
PORTULACACEAE (Purslane family)	
Portulaca oleraceae L.	Common purslane
PRIMULACEAE (Primrose family)	
Anagallis arvensis L.	Scarlet pimpernel
MARTYNIACEAE (Martynea family)	
Proboscidea louisianica (Mill.) Thell.	Proboscis flower
ASTERACEAE (Aster family)	
Acroptilon repens	Russian knapweed
Ageratum conyzoides L.	Undetermined
Ambrosia artemisiifolia L.	Ragweed
Ambrosia hispida Pursh	Undetermined
Arctium minus (Hill) Bernh.	Common burdock
Arctium lappa L.	Great burdock
Arctotis stoechadifolia Bergius	African daisy
Aster sp.	Aster
Bellis perennis L.	English daisy
*Bidens biternata (*Lour.) Merr. & Scherff.	Undetermined

Table 1. (continued)

Latin binomial	Common name
Brachycombe iberidifolia Benth.	Swan River daisy
Calendula officinalis L.	Pot marigold
Callistephus chinensis (L.) Hees	China-aster
Carthamus tinctorius L.	Safflower
Centaurea cyanus L.	Bachelor’s button
Centaurea dealbata Willd.	Undetermined
Centaurea diffusa Lam.	Diffuse knapweed
Centaurea montana L.	Mountain bluet
Centaurea moschata L.	Sweet sultan
Centaurea solstitialis L.	Yellow star-thistle
Centaurea sp.	Knapweed
Chrysanthemum cinerariifolium (Trever) viz.	Dalmatian pyrethrum
Chrysanthemum coccineum Willd.	Common pyrethrum
Chrysanthemum coronarium L. var. *spatiosum*	Undetermined
Chrysanthemum leucanthemum L.	Ox-eye daisy
var. *pinnatifidum* Lecoq. & Lamotte	
Chrysanthemum maximum Ramond	Daisy
Chrysanthemum morifolium Ramat.	Florists’ chrysanthemum
Chrysanthemum spp.	Chrysanthemum
Cichorium endivia L.	Endive
Cichorium intybus L.	Chicory
Cirsium arvense (L.) Scop.	Canada Thistle
Cirsium vulgare (Savi) Ten.	Bull thistle
Cnicus arvensis Hoffm.	Thistle
Cnicus benedictus L.	Blessed thistle
Cnicus spp.	Blessed thistle
Coreopsis grandiflora Hagg. ex Sweet1969	Tickseed
Coreopsis spp.	Tickseed
Coreopsis stillmani (Gray) Blake	Tickseed
Coreopsis tinctoria Nutt.	Calliopsis
Cosmos bipinnatus Cay.	Cosmos
Crepis japonica (L.) Benth.	Hawk’s beard
Cynara scolymus L.	Artichoke
Dahlia pinnata Cav.	Garden dahlia
Dahlia pluvialis (L.) Moench.	Undetermined
Dahlia spp.	Dahlia
Dimorphotheca aurantiaca D.C.	Cape marigold
Dimorphotheca sp. Moench.	Cape marigold
Erechtites hieracifolia (L.) Raf.	Pilewort
Erigeron annuus (L.) Pers.	Sweet scabious
Erigeron canadensis L.	Hog-weed
Gaillardia pulchella Foug.	Firewheel

Table 1. (continued)

Latin binomial	Common name
Gaillardia sp.	Gaillardia
Galinsoga parviflora Cav.	Small-flowered galinsoga
Gazania rigens (L.) Gaertn.	Treasure flower
Gerbera jamesonii Bolus	Transvaal daisy
Gerbera spp.	Gerbera
Gnaphalium purpureum L.	Purple cudweed
Gynura sp.	Undetermined
Helianthus annuus L.	Sunflower
Helianthus tuberosus L.	Jerusalem artichoke
Helichrysum bracteatum (Venten.) Andr.	Undetermined
Helichrysum sp.	Strawflower
Helipterum almcans (Cunn.) D.C.	Everlasting
Helipterum roseum (Hook.) Benth.	Paper flower
Ixeris dentata (Thunb) Nakai	Undetermined
Iva xanthifolia Nutt.	False ragweed
Iva sp.	Marsh-elder
Lactuca sativa L.	Garden lettuce
Lactuca sativa var. *capitata* L.	Head lettuce
Lactuca sativa var. *crispa* L.	Leaf lettuce
Lactuca sativa var. *longifolia* Lam.	Romaine lettuce
Lactuca serriola L.	Prickly lettuce
Lactuca spp.	Lettuce
Liatris sp.	Gay-feather
Onopordum acanthium L.	Scotch thistle
Osteospermum ecklonis (D.C.) Norl.	African daisy
Osteospermum fruiticosum (L.) Norl.	African daisy
Parthenium argentatum Gray	Guayule
Rudbeckia laciniata (L.) Per.	Coneflower
Rudbeckia laciniata (L.) var. *hortensis* Bailey	Golden-glow
Scorzonera hispanica L.	Black salsify
Scorzonera sp.	Salsify
Senecio cruentus (Masson) D.C.	Florists' cineraria
Senecio spp.	Groundsel
Senecio vulgaris L.	Groundsel
Silybum marianum (L.) Gaertn.	Milk thistle
Solidago canadensis L. var. *salebrosa* (Piper) Jones	Goldenrod
Sonchus arvensis L.	Field sow-thistle
Sonchus asper (L.) Hill.	Spiny sow-thistle
Sonchus oleraceus L.	Common sow-thistle
Sonchus spp.	Sow-thistle
Stokesia laevis (Hill.) Greene	Stokes' aster
Tagetes erecta L.	African marigold

Table 1. (continued)

Latin binomial	Common name
Tagetes patula L.	African marigold
Tagetes sp.	Marigold
Tagetes tenuifolia Cav.	Signet marigold
Taraxacum kok-saghyz Rodin.	Russian dandelion
Taraxacum officinale Wiggers	Common dandelion
Tragopogon porrifolius L.	Salsify
Venidium decurrens Less.	Undetermined
Venidium fastiuosum (Jacq.) Stapf.	Cape daisy
Verbesina spp.	Crown-beard
Xanthium pensylvanicum Wallr.	Cocklebur
Zinnia elegans Jacq. (Z. elegans L.)	Zinnia
Zinnia spp.	Zinnia
BEGONIACEAE (Begonia family)	
Begonia tuberhybrida Voss	Begonia
BERBERIDACEAE (Barberry family)	
Berberis sp.	Barberry
BORAGINACEAE (Borage family)	
Anchusa azurea Mill.	Alkanet (Buglossum)
Anchusa capensis Thunb.	Bugloss
Cynoglossum amabile Stapf. & Drumm.	Chinese forget-me-not
Mertensia lanceolata (Pursh.) D.C.	Bluebell
Myosotis arvensis (L.) Hill	Forget-me-not
Myosotis scorpiodes L.	Forget-me-not
Myosotis sp.	Forget-me-not
Myosotis sylvatica Hoffm.	Garden forget-me-not
RANUNCULACEAE (Crowfoot family)	
Aconitum carmichaelii Debeaux	Azure monkshood
Anemone coronaria L.	Poppy anemone
Aquilegia vulgaris L.	European crowfoot
Aquilegia spp.	Columbine
Consolida orientalis (Gray) Schrod.	Rocket larkspur
Delphinium cheilanthum Fisch.	Garland larkspur
Delphinium cultorum Voss	Larkspur
Delphinium elatum L.	Candle larkspur
Delphinium grandiflorum L.	Bouquet larkspur
Delphinium sp.	Larkspur
Ranunculus asiaticus L.	Persian buttercup
Ranunculus sp.	Buttercup
Trollius sp.	Globeflower
SCROPHULARIACEAE (Figwort family)	
Antirrhinum majus L.	Common snapdragon
Calceolaria crenatiflora Cav.	Slipperwort

Table 1. (continued)

Latin binomial	Common name
Calceolaria sp.	Slipperwort
Digitalis purpurea L.	Common foxglove
Linaria canadensis (L.) Dum	Blue toadflax
Linaria spp.	Toadflax
Linaria vulgaris Mill.	Butter-and-eggs
Nemesia sp.	Undetermined
Paulownia sp.	Undetermined
Verbascum blattaria L.	Moth mullein
THEACEAE (Camellia family)	
Camellia japonica L.	Camellia
Camellia sp.	Camellia
TILIACEAE (Basswood family)	
Corchoris capsularis L.	Jute
TROPAEOLACEAE (Tropaeolum family)	
Tropaeolum majus L.	Garden nasturtium
Tropaeolum sp.	Nasturtium
URTICACEAE (Nettle family)	
Urtica dioica L. ssp. *gracilis* (Ait.) Selander var. *gracilis*	Stinging nettle
Urtica gracilis Ait.	Nettle
Urtica sp.	Nettle
VALERIANACEAE (Valerian family)	
Valeriana officinalis L.	Common valerian
VIOLACEAE (Violet family)	
Viola odorata L.	Sweet violet
Viola sp.	Pansy
ARACEAE (Arum family)	
Epipremnum aureum (Linden & Andre) Bunt.	Pothos
Philodendron scandens Koch & Sello	Heart-leaf philodendron
Philodendron selloum C. Koch	Philodendron
ACANTHACEAE (Acanthus family)	
Hemigraphis alternata (Bum.) Anderson	Red ivy
ACTINIDIACEAE (Actinidia family)	
Actinidia chinensis Planch.	Chinese gooseberry
AIZOACEAE (Carpet-weed family)	
Dorotheanthus belliformis (Burm.)	Livingstone daisy
Tetragonia tetragonioides (Pall.) Kuntze	New Zealand spinach
AMARANTHACEAE (Amaranth family)	
Amaranthus retroflexus L.	Redroot pigweed
Amaranthus sp.	Undetermined
Celosia sp.	Cock’s-comb
APOCYNACEAE (Dogbane family)	
Catharanthus roseus (L.) Don	Madagascar periwinkle

Table 1. (continued)

Latin binomial	Common name
Vinca minor L.	Common periwinkle
ARALIACEAE (Ginseng family)	
Aralia cordata Thurb.	Spikenard
Hedera helix L.	English ivy
Panax pseudoginseng Wallich	Ginseng
Panax quinquefolius L.	American ginseng
Schefflera arboricola Hayata	Undetermined
ARISTOLOCHIACEAE (Birthwort family)	
Aristolochia durior Hill	Dutchman's pipe
Asarum canadense L.	Wild ginger
ASCLEPIADACEAE (Milkweed family)	
Asclepias sp.	Milkweed
Stephanotis floribunda Brongn.	Undetermined
CAPPARIDACEAE (Caper family)	
Cleome viscosa L.	Tickweed
CARYOPHYLLACEAE (Pink family)	
Dianthus caryophyllus L.	Carnation
Gypsophila paniculata L.	Baby's-breath
Stellaria media (L.) Cyr.	Chickweed
CELASTRACEAE (Staff-tree family)	
Euonymus alata (Thunb.) Siebold	Winged spindle-tree
Euonymus alata (Thunb.) Siebold var. *compacta*	Winged spindle-tree
CYPERACEAE (Sedge family)	
Cyperus rotundus L.	Nut grass
DIPSACACEAE (Teasel family)	
Dipsacus fullonum L.	Common teasel
FAGACEAE (Beech family)	
Quercus sp.	Oak
FUMARIACEAE (Fumitory family)	
Dicentra spectabilis (L.) Lem.	Bleeding heart
GENTIANACEAE (Gentian family)	
Gentiana lutea L.	Yellow gentian
GERANIACEAE (Geranium family)	
Pelargonium hortorum Bailey	Zonal geranium
Pelargonium spp.	Pelargonium
GESNERIACEAE (Gesneria family)	
Sinningia speciosa (Lodd.) Hiern.	Gloxinia
HIPPOCASTANACEAE (Horse Chestnut family)	
Sculus hippocastanum L.	Horse chestnut
HYDRANGEACEAE (Hydrangea family)	
Hydrangea sp.	Hydrangea

Table 1. (continued)

Latin binomial	Common name
JUGLANDACEAE (Walnut family)	
Engelhardtia spicata Blume	Undetermined
LAURACEAE (Laural family)	
Persea americana Mill.	Avocado
Persea borbonia (L.) Spreng	Laurel tree
MYRSINACEAE (Myrsine family)	
Ardisia crenta Sims	Coralberry
Ardisia crispa (Thunb.) A.DC	Ardisia
MYRTACEAE (Myrtle family)	
Eucalyptus sp.	Undetermined
OLEACEAE (Olive family)	
Forsythia sp.	Golden-bells
Forsythia suspensa (Thunb.) Vahl.	Golden-bells
Forsythia viridissima Lindl.	Golden-bells
Syringa vulgaris L.	Common lilac
ONAGRACEAE (Primrose family)	
Fuchsia sp.	Undetermined
Oenothera sp.	Evening primrose
OROBANCHACEAE (Broom-rape family)	
Orobanche cernua Loefl.	Broomrape
Orobanche spp.	Broomrape
PAEONIACEAE (Paeony family)	
Paeonia lactiflora Pall.	Garden peony
Paeonia officinalis L. Peony	
POLYPODIACEAE (Fern family)	
Rumohra adaintiformis (G. Forst.) Ching	Leather leaf fern
SALVINIACEAE (Salvinia family)	
Azolla pinnata R. Br.	Mosquito- fern

Although most hosts are found in the subclass Dicotyledonae of the Angiospermae class, the table shows the large range of host species from 75 different (Boland and Hall, 1994). Some weed species are hosts of *Sclerotinia sclerotiorum* including *Cirsium arvense* (Canada thistle), *Ambrosia artemisiifolia* (common ragweed), *Taraxacum officinale* (dandelion), *Amaranthus retroflexus* (redroot pigweed), and *Abutilon theophrasti* (velvetleaf) (Mueller et al., 2015a). There has been research in utilizing *Sclerotinia sclerotiorum* as a biological control of host weed species, unfortunately, with the potential of exploiting non-target hosts to the pathogen as well (Boland and Hall, 1994).

Temperature and moisture

Sclerotinia sclerotiorum is a fungus that thrives in cool, moist conditions (Hefty, 2017). For infection to begin, germination of sclerotia is triggered by rainfall (Twengström et al., 1998). Germination typically occurs after a period of nearly saturated soils, cool temperatures, and can be aided by the crop canopy shading the soil, slowing the soil drying process (Heffer Link and Johnson, 2007). It has been suggested that sclerotia benefit from a period of drying at or near the soil surface causing germination when the soil moisture returns to near field capacity (Abawi and Grogan, 1979). Moisture is an important environmental variable for many aspects of the life cycle of *Sclerotia sclerotiorum.* Not only can greater yield and quality losses occur in wetter areas, but leaf wetness is required for infection of many of the host crops (Young et al., 2004). It is suggested that roughly 48-72 hours of continued leaf wetness and long periods of available free moisture is maintained for infection of *Sclerotinia sclerotiorum* to occur (Abawi and Grogan, 1979).

Although moisture is of high concern for germination, temperature, although not a limiting factor, is also important. At a constant, optimum temperature of 20-25°C, ascospores germinate and grow as well as lesions begin to initiate and develop (Abawi and Grogan, 1979). Even with a wide range of temperatures for infection, no infection has occurred at 5 or 30°C (Young et al., 2004). During flowering, if the temperature is above 29.4°C, there is a significantly lower risk of disease development (Giesler, 2016).

Optimum temperatures for infection may depend on the host crops as well. The optimum temperature for infection of soybeans is 20-25°C (Abawi and Grogan, 1979). For lettuce, the optimum temperatures for disease development were between 16-27°C (Young et al., 2004). For stored carrots, the optimum temperature is 13-18°C as long as there is free moisture on the root surface allowing infection (McDonald et al., 2004).

There are localities that are considered hot and dry that also see the occurrence of *Sclerotinia sclerotiorum* because these areas are growing susceptible hosts during cooler months of the year (Purdy, 1979).

LIFE CYCLE

Sclerotinia sclerotiorum acts as both a soilborne and airborne pathogen being able to infect above ground and below ground plant parts (Abawi and Grogan, 1979). Because this pathogen is monocyclic, there is only one primary mode of infection depending on type of infection incited (Heffer Link and Johnson, 2007). By understanding the epidemiology of *Sclerotinia sclerotiorum*, there is an improved chance of forecasting and monitoring potential infection and dispersal of this disease.

Dispersion methods

Sclerotinia sclerotiorum has two methods of germination for dispersion, carpogenic germination and myceliogenic germination (Heffer Link and Johnson, 2007). Carpogenic germination produces a mushroom-like body called apothecium that produces spores called ascospores while myceliogenic germination produces filaments that make up mycelia directly from sclerotia (Canola Council of Canada, 2014). Apothecia is a tan, cup shaped structure that reaches 1/8-1/4 inch in diameter within the top two inches of the soil (Mueller et al., 2015b). Plant-to-plant infection happens only through direct hyphal growth from previously infected tissue (Abawi and Grogan, 1979). It is possible for *Sclerotinia sclerotiorum* to spread from plant to plant but it rarely occurs (Heffer Link and Johnson, 2007).

Following the carpogenic germination of a sclerotium and under certain environmental conditions, the apothecium emerges and produces ascospores (Bolton et al., 2006). Apothecial development requires 10 days of continuous moisture but will not develop if there is the slightest change in moisture tension caused by drying soils (Abawi and Grogan, 1979). The apothecia will only grow from sclerotia and a single sclerotium can produce up to 15 apothecia (Canola Council of Canada, 2014). Generally, there is a change in relative humidity or a physical disturbance forcibly releasing ascospores from each ascus within an apothecium (Bolton et al., 2006). The dispersion of the ascospores is greater than one centimeter, allowing for the spores to move through the boundary layer, the still layer of air near the soil surface, to where the wind can carry disperse the pathogen (Abawi and Grogan, 1979). Each apothecium can release over 10 million ascospores over several days. The ascospores are dispersed by wind and can only survive a few days after release (Heffer Link and Johnson, 2007). The longest dispersal of ascospores from *Sclerotinia sclerotiorum* is several kilometers (Abawi and Grogan, 1979).

In myceliogenic germination, plant exudates stimulate hyphal strand growth from sclerotia (Heffer Link and Johnson, 2007). This type of germination allows for below ground infection from the soilborne sclerotia (Abawi and Grogan, 1979). Myceliogenic germination is not as common as carpogenic germination and typically only occurs in a few crops such as sunflowers, *Daucus carota* (carrots), and other vegetables (Bolton et al., 2006). Under rare occasions, mycelium can infect soybeans and bean species (Abawi and Grogan, 1979). As long as there is adequate moisture and an energy source, mycelium moves from colonized areas to the healthy host tissue composed of stems, pods, leaves, etc. (Heffer Link and Johnson, 2007). The mycelium grows and penetrates the cuticle of a host plant through the stomata, by mechanical force, or using an enzyme (Bolton et al., 2006). Whether myceliogenic or carpogenic germination, the pathogen requires a nutrient source in order to complete the disease cycle.

Infection sites

The first tissues generally infected by *Sclerotinia sclerotiorum* ascospores are the highly susceptible flower petals and senescing leaves (Heffer Link and Johnson, 2007). Typically, spores are not able to infect leaves and stems directly; they utilize the dead petals and other organic material as a food source to stimulate hyphal production for host penetration. The release of ascospores can be appropriately timed to infect a host tissue soon after early bloom to ensure a food source from the lower stem of dying leaves and petals (Canola Council of Canada, 2014). The spores also infect other weak areas of host plants such as mechanically damaged or necrotic lesions (Abawi and Grogan, 1979). Cabbage plants and tobacco seedlings are two host plants readily infected by ascospores through wounds (Heffer Link and Johnson, 2007). Some literature has reported ascospores penetrating healthy host tissue directly and establishing infection, however, this is a rare type of infection (Purdy, 1979). In order for the ascospores to adhere to the host plant, the spores are covered in a sticky mucilage (Bolton et al., 2006). The ascospores are capable of completely colonizing blossoms with 2-3 days, encouraging spread of the disease to healthy host tissue by mycelial growth (Abawi and Grogan, 1979).

Similar to carpogenic germination, hyphal germination must first invade non-living organic matter before infection can occur (Purdy, 1979). Root tissue is particularly susceptible to this type of germination, especially if in direct contact with sclerotia (Canola Council of Canada, 2014).

Once the leaves, blossoms, and leaf axils are infected, *Sclerotinia sclerotiorum* spreads into the stem (Canola Council of Canada, 2014). After infection, a thick mycelium may form on both the inside and outside of the host tissue (Heffer Link and Johnson, 2007). After the mycelia meet a nutrient-limited environment, sclerotia are produced (Bolton et al., 2006). Within 7-10 days, the mycelial growth is capable of producing numerous sclerotia on or within the host plant (Abawi and Grogan, 1979).

Survival and overwintering structures

Sclerotia are the hard, black survival structures of *Sclerotinia sclerotiorum* ranging in size of 1/16-1 inch (Mueller et al., 2015b). As the survival structure of *Sclerotinia sclerotiorum*, sclerotia are able to remain viable for eight years in the soil waiting for optimum conditions (Bolton et al., 2006). The three stages of sclerotial development are: initiation (aggregation of hyphal formation), development (hyphal growth), and maturation (melanin deposit and surface delimitation) (Bolton et al., 2006). Sclerotia are formed from mycelium on the plant tissue or within the stem or other plant parts of the host species. As the host plant or its plant part dies, the sclerotia fall to soil where they can remain for many years (Heffer Link and Johnson, 2007). Sclerotia act as both the survival structures and the inoculum in initiating the disease (Bolton et al., 2006). The size of sclerotia allows for the inoculum to be mixed in with seed, allowing for distribution in new, non-infected areas (Canola Council of Canada, 2014). Sclerotia are only functional if they have been preconditioned by a certain amount of time (depends on the isolate) and are within the top 2-3 centimeters of the soil because of the inability of apothecia or hyphal growth beyond that (Abawi and Grogan, 1979).

It is important to note that survival times of other growth stages play a vital role in disease development. Depending on the environmental conditions, ascospores are able to survive on plant tissue for two weeks (Bolton et al., 2006). The spores are able to wait for wet conditions or energy sources that are conducive for infection (Abawi and Grogan, 1979).

DAMAGE, RISK ASSESSMENT, AND SCOUTING

The disease triangle describes the three components necessary for disease development: the pathogen, the host, and the environmental conditions (Francl, 2001). Using disease-forecasting models that incorporate scouting, sampling methods, environmental and crop factors, and field history can assist in making management decisions.

Field history and weather patterns forecasting white mold

By understanding the field history and weather patterns associated with *Sclerotinia sclerotiorum*, disease-forecasting models can be used to predict initial occurrence, subsequent development, and the potential need for disease management applications (McDonald et al., 2004). There are no forecasting systems available that are completely accurate, but they do provide direction when deciding management approaches (Canola Council of Canada, 2014). Disease-forecasting models should follow each individual crop basis because of the etiology of diseases on certain crops. For example, Sclerotinia rot of cabbage usually occurs late season while pink rot of celery can develop at any time (McDonald et al., 2004). Some of the models used for predicting disease assume continuous presence of the pathogen; even when environmental conditions favor disease development, there needs to be inoculum present (Bom and Boland, 2000). By understanding all three components, disease-forecasting models are able to monitor the factors associated with *Sclerotinia sclerotiorum* development.

Crop variables such as crop height, canopy density, canopy enclosure, senescing leaves and blossoms, varietal susceptibility, blossom development, and cropping history should be utilized to assess the risk of disease (Bom and Boland, 2000). Environmental factors such as rainfall, air temperature, soil temperature, heat units, light penetration, leaf wetness, and soil moisture should be monitored (Canola Council of Canada, 2014). Soil moisture is the environmental variable that is most closely associated with disease development (Bom and Boland, 2000). By understanding the factors involved in development, some methods of disease forecasting were developed and researched.

Depending on the crop, there have been several proposed prediction models utilized to forecast disease created by *Sclerotinia sclerotiorum* (Bom and Boland, 2000). An important component of disease forecasting is measuring the primary inoculant. Several methods for measuring inoculum are: estimating the presence of sclerotia, apothecia, ascospores, and colonized petals (McDonald et al., 2004). Another method for forecasting disease development in *Brassica napus* (oilseed rape) was the Canadian Sclerotinia checklist, however, there is no evaluation of the accuracy of this model (Twengström et al., 1998). Another method that used in Sweden is the risk point system. This system gives points to the factors associated with *Sclerotinia sclerotiorum* and compared to predetermined thresholds. The thresholds less than 60 risk points suggested that no fungicide application be made, between 60-100 risk points was the uncertain zone, and above 100 risk points fungicide application is recommended (Twengström et al., 1998). Petal infestation and apothecia counts have been proposed methods of forecasting disease, but these methods are timely and costly (Bom and Boland, 2000). Being that there is such a wide range of hosts of *Sclerotinia sclerotiorum*, disease-forecasting models need to be created following host specific protocols.

Regardless of the number of forecasting models for *Sclerotinia sclerotiorum*, there are few examples of forecasting models that can be applied in all countries (McDonald et al., 2004). Forecasting models have been studied, developed, and evaluated in Denmark, Germany, Canada, and Sweden, but the accuracy of the forecasting models are still not fully satisfactory (Twengström et al., 1998). Some reasoning for the lack of development or implementation of forecasting models to meet satisfaction may be variations in epidemic severity, lack of registered fungicides, little to no infrastructure to deliver the disease-forecasting models, decline in the use of integrated pest management programs, and fewer employed plant pathologists in private and public sectors (McDonald et al., 2004). Regardless of specific forecasting models, tracking disease levels across different environmental conditions conducive to disease development is beneficial in predicting disease incidences (Mueller et al., 2015a).

Disease incidence levels

Estimates of the economically important levels of *Sclerotinia sclerotiorum* vary dramatically amongst studies (McDonald et al., 2004). Instead of utilizing an economic threshold, assessing the level of infection is determined by the disease incidence level. The disease incidence level is estimated by examining different areas of a field and quantified by dividing the number of plants infected with *Sclerotinia sclerotiorum* by the total number of plants assessed (Esker, 2017). The disease incidence is given a percentage rating (Makowski et al., 2005).

Although disease incidence varies greatly among fields, regions, and years, when applied with a forecasting model, predicting disease severity proves as a reliable source for deciding management strategies (Twengström et al., 1998). However, disease incidences are rarely as severe as many think. There are circumstances where sclerotia levels are high but no disease incidences occur, and there are other circumstances where the fields did not appear to have any inoculum, yet they developed high incidence of disease (McDonald et al., 2004). Depending on the prediction model used, there may be some predetermined thresholds for making management decisions. When following a risk point, checklist, or risk indicator disease-forecasting model, predetermined decision thresholds can be used for deciding if a fungicide application is recommended (Makowski et al., 2005).

Scouting and sampling methods

High yield potential, dense canopy, susceptible varieties, field history, and environmental conditions conducive to disease development are seasonal and long-term factors that favor *Sclerotinia sclerotiorum* (Mueller et al., 2015b). Scouting should begin in low, wet spots of a field that provide favorable conditions for sclerotia germination, fields with a history of disease, and fields that had nearby host species with some level of disease development (Canola Council of Canada, 2014). Parts of the field that experiences less wind disturbance, tree lines and dense canopies, should also be scouted early on (Mueller et al., 2015b). Scouting for signs and symptoms needs to be done diligently to predict disease development and prevent disease epidemic (Bayer, 2018). Post-harvest scouting involves checking seed lots for sclerotia and infected seeds that are typically smaller, lighter, and have mycelium on them (Mueller et al., 2015b). Scouting in a timely manner assists in deciding on sampling methods as well as management applications.

When sampling fields, disease incidence has been associated with the prevalence and distribution of apothecia of *Sclerotinia sclerotiorum* (McDonald et al., 2004). One method of sampling is by counting sclerotia or apothecia. Each apothecium produces large numbers of spores, so relatively few are needed to caused localized disease epidemics; however, the apothecium counts only provide immediate results and do not include other important variables for disease incidence (Bom and Boland, 2000). *Sclerotinia sclerotiorum* epidemics are sporadic in their development, and by monitoring the crop growth stage, the presence of inoculum, and environmental conditions conducive to disease development, disease-forecasting models can prove beneficial in utilizing management strategies (McDonald et al., 2004).

MANAGEMENT

The long term survival of sclerotia and being able to produce air-borne ascospores makes it difficult to control *Sclerotinia sclerotiorum* (Smolińska and Kowalska, 2018). Disease development can be erratic and difficult to control once signs and symptoms are observed (McDonald et al., 2004). Environmental monitoring and disease-forecasting systems can improve management methods by making the best management decision to reduce the impact of *Sclerotinia sclerotiorum* (Esker, 2017).

Cultural practices

As for reducing the number of sclerotia in the soil, cultural practices are the least harmful to the environment (Smolińska and Kowalska, 2018). Some of the cultural practices used by growers are crop rotation, planting populations, tillage, row width, and breeding efforts.

Crop rotation consists of a minimum of two to three years of a nonhost crop, such as corn, wheat, barley, or oats, in order to minimize inoculum in the soil (Mueller et al., 2015a). Sclerotia have the potential to germinate in a nonhost crop, but without successive host infection, new sclerotia are not produced or added to the soil. Crop rotation is most effective before *Sclerotinia sclerotiorum* becomes a problem (Heffer Link and Johnson, 2007).

This fungus has a wide host range that includes many weed species, if the weeds are not properly treated, rotation to a nonhost crop could be nullified (Westphal et al., 2015). Besides planting nonhost crops, controlling the planting population will have an effect on *Sclerotinia sclerotiorum*. High plant populations create dense canopies that close sooner (Mueller et al., 2015a). In a field with a history of the fungal disease, 125,000 to 150,000 plants per acre are recommended and 200,000 plants per acre should always be avoided (Westphal et al., 2015). Utilization of precision seeding decreases the amount of clustered plants while improving the plant spacing (Heffer Link and Johnson, 2007). Another factor of plant spacing is row width and its ability to allow air to circulate throughout the canopy, especially during the beginning of flowering (Westphal et al., 2015). Early planting and varietal maturity may also play a role in disease incidences. Late-maturing varieties of soybeans tend to have a bushy architecture and can lodge, contributing to a closed canopy (Mueller et al., 2015a). Early-maturing cultivars have a more upright growth habit, generally allowing for more air circulation resulting in less disease (Heffer Link and Johnson, 2007).

Fertility and irrigation have the potential to have an effect on disease incidence. Nitrogen-rich manures and fertilizers favor *Sclerotinia sclerotiorum* development by increasing plant growth and expedited canopy closure (Mueller et al., 2015a). The frequencies of leaf wetness for 12-24 hour periods caused by irrigation should be reduced during the bloom period to minimize disease development (Heffer Link and Johnson, 2007). Cultural control through deep tillage may initially reduce disease development but since sclerotia can remain viable in the plow layer for more than three years, subsequent tillage will return the buried sclerotia to the surface (Mueller et al., 2015a). Tillage may also contribute to the dispersal of inoculum if machinery is not well cleaned (Heffer Link and Johnson, 2007). For this reason, it is important to harvest disease-infested fields after harvesting healthy fields, or properly clean the harvesting equipment before entering healthy fields (Bayer, 2015).

Although high levels of resistance to *Sclerotinia sclerotiorum* is lacking in many major crops, breeders do rely on partial resistance as an economically useful disease control (Bolton et al., 2006). For soybeans in particular, germplasm selection often involves only a single isolate. The isolate diversity of *Sclerotinia sclerotiorum* was investigated using growth patterns, aggressive properties, mycelial compatibility groups, and the production of oxalic acid as a factor of *Sclerotinia sclerotiorum*. Controlled-environment resistance soybeans typically uses one or two aggressive isolates of *Sclerotinia sclerotiorum*. Since diverse isolates are found in soybean fields, soybean genotypes should be selected for using the appropriate isolates. Studies of *Brassica* spp. is also considering the potential benefits of using a diverse set of isolates (Willbur et al., 2017).

Pesticides

Fungicides are the most successful and effective means of control of *Sclerotinia sclerotiorum* (Smolińska and Kowalska, 2018). Some crops, such as soybeans and potatoes, may have sufficient control from a single fungicide application, while crops, like *Phaseolus limensis* (lima beans), may need 2-3 fungicide applications for the longer blooming period (Heffer Link and Johnson, 2007). Foliar applied herbicides and fungicides have efficacy against the fungus, but none offers complete control (Mueller et al., 2015a). The active ingredients in fungicides for activity on *Sclerotinia sclerotiorum* are: boscalid, fluazinam, fluxapyroxad, pyraclostrobin, penthiopyrad, picoxystrobin, prothioconazole, prothioconazole and trifloxystrobin, tetraconazole, and thiophanate methyl (Smolińska and Kowalska, 2018).

Herbicides that contain the active ingredient of lactofen can be used as part of an integrated management system in some crops, such as soybeans. Lactofen modifies the soybean canopy by delaying or reducing flowering. This results in altering the potential infection sites for *Sclerotinia sclerotiorum* (Mueller et al., 2015a).

Application rates, timing, and method are crucial to improving the amount of control. Fungicides need to be applied as protectants against infection because the fungicides are more preventative than curative measures of control (Heffer Link and Johnson, 2007). The primary treatments of fungicide need to be made prior to canopy closes to get the active ingredient to the targets of senescing leaves and blooms. Following manufacturer’s recommendations of spray volume and environmental, as well as the use of flat fan nozzles increases the foliar effectiveness by adequate plant coverage and canopy penetration (Bayer, 2018).

Table 2. Pesticides currently registered for suppression or control of *Sclerotinia sclerotiorum* in *Glycine max* (adapted from Mueller et al., 2015a)

Product type	Active ingredient	Product name
Fungicide	boscalid	Endura®, Lance®
Fungicide	fluazinam	Omega®, Allegro®
Fungicide	fluxapyroxad and pyraclostrobin	Priaxor®
Fungicide	penthiopyrad	Vertisan®
Fungicide	picoxystrobin	Aproach™
Fungicide	prothioconazole	Proline®
Fungicide	prothioconazole and trifloxystrobin	Stratego®YLD
Fungicide	tetraconazole	Domark®
Fungicide	thiophanate methyl	Topsin®, Incognito®
Herbicide	lactofen	Cobra®, Phoenix ™

Biological control

The abiotic and biotic environmental factors have an affect on the biocontrol agents, leaving the agents less effective than synthetic pesticides (Smolińska and Kowalska, 2018). Sclerotia are the most important survival structures of *Sclerotinia sclerotiorum*. Microorganisms that can neutralize the sclerotia have been the focus for biocontrol using fungi (Smolińska and Kowalska, 2018). The parasitic fungus *Coniothyrium minitans* and fungi of the genus *Trichoderma* have had studies done with them. This pathogenic fungi are able to colonize their host, *Sclerotinia sclerotiorum*, by production of cell-wall-degrading enzymes such as: pectinases, β-1,3-glucanases, glycosidases, cellulases, xylanases, cutinases, chitinases, and proteases (Bolton et al., 2006). Contans®WG is a commercial formulation of *Coniothyrium minitans* and is known to degrade the sclerotia in the soil, reducing the damage caused by *Sclerotinia sclerotiorum* (Huang and Erickson, 2008). Fungi of the genus *Trichoderma* are known for their rapid growth and abundant production of spores that are used to control the pathogen by mechanisms of mycoparasitism, antibiosis, and systemically induced resistance. Some examples of *Trichoderma* species and their related crop are: *Trichoderma asperellum* and *Phaseolus* spp. (common bean), *Trichoderma hamatum* reduction in disease of cabbage, and the positive effect *Trichoderma harzianum* has on *Cucumis sativus* (cucumber) (Smolińska and Kowalska, 2018).

Certain bacterial genera can be used as a biological control against *Sclerotinia sclerotiorum* by inhibiting the germination of ascospores by production of antimicrobial substances or direct growth on the ascospores (Huang and Erickson, 2008). The two main genera of bacteria used for antagonistic activity against *Sclerotinia sclerotiorum* are *Bacillus* and *Pseudomonas*. Both *Bacillus cereus* and *Bacillus subtilis* reduced hyphal growth in sunflowers, while *Bacillus subtilis* was utilized as seed coating on oilseed rape to minimize disease. The biological activity of induced systemic resistance is triggered by compounds produced by *Bacillus* spp. (Smolińska and Kowalska, 2018).

Table 3. Microorganisms with antagonistic activity against *Sclerotinia sclerotiorum* (adapted from Smolińska and Kowalska, 2018).

Microorganism type	Species
Fungi	*Alternaria alternata*
Fungi	*Aspergillus niger*
Fungi	*Aspergillus ustus*
Fungi	*Coniothyrium minitans*
Fungi	*Drechslera* sp.
Fungi	*Epicoccum purpurascens*
Fungi	*Fusarium graminearum*
Fungi	*Fusarium heterosporum*
Fungi	*Fusarium oxysporum*
Fungi	*Gliocladium virens*
Fungi	*Gliocladium roseum*
Fungi	*Microsphaeropsis ochracea*
Fungi	*Myrothecium verrucaria*
Fungi	*Penicillium citrinum*
Fungi	*Penicillium funiculosum*
Fungi	*Penicillium pallidum*
Fungi	*Sporidesmium sclerotivorum*
Fungi	*Streptomyces lydicus*
Fungi	*Talaromyces flavus*
Fungi	*Teratosperma oligocladum*
Fungi	*Trichoderma asperellum*
Fungi	*Trichoderma hamatum*
Fungi	*Trichoderma harzianum*
Fungi	*Trichoderma atroviride*
Fungi	*Trichoderma koningii*
Fungi	*Trichoderma virens*
Fungi	*Trichoderma stromatica*
Fungi	*Ulocladium atrum*
Bacteria	*Bacillus subtilis*

Table 3. (continued)

Microorganism type	Species
Bacteria	*Bacillus megaterium*
Bacteria	*Bacillus amyloliquefaciens*
Bacteria	*Bacillus cereus*
Bacteria	*Erwinia herbicola*
Bacteria	*Pseudomonas chlororaphis*
Bacteria	*Pseudomonas fluorescens*
Bacteria	*Pseudomonas putida*
Bacteria	*Pseudomonas cepacia*
Bacteria	*Pseudomonas brassicacearum*
Bacteria	*Serraria plymuthica*

Another type of biological control is the monitoring and amending of organic materials in the soil. These materials act as sources of nutrients for the microorganisms in the soil, but they may also have negative effects that increase the pathogen population and stimulate carpogenic germination of the sclerotia. Applying organic materials that contain antagonistic microorganisms can help eliminate *Sclerotinia sclerotiorum* (Smolińska and Kowalska, 2018).

CONCLUSION

Although research continues on *Sclerotinia sclerotiorum*, complete resistance and curative measures of this disease are not available. Worldwide distribution along with over 400 species of hosts continue to make it difficult in creating disease-forecasting models. With basic knowledge of the signs and symptoms of the fungus, along with awareness of the favorable environmental conditions and life cycles of the host species, preventing *Sclerotinia sclerotiorum* is a possibility. Familiarity of field history, disease dispersion methods, and continued scouting and sampling techniques should be included in an integrated management program that includes cultural, chemical, and biological control methods. Prevention of *Sclerotinia sclerotiorum* is the most effective way to manage the spread of this devastating disease.

A better understanding of the germination and dormancy requirements of sclerotia caused by *Sclerotinia sclerotiorum* is needed to improve disease-forecasting models. By utilizing infrared technology during scouting, differences in plant tissue temperature may be able to differentiate healthy host tissue from infected tissue early on.

Other potential research could test different isolates for the preconditioning requirements to understand the dormancy and germinating needs of the sclerotia.

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